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Seabed-Structure Interaction

Workshop Report and Recommendations for Future Research

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SUMMARY OF RECOMMENDED RESEARCH THRUSTS

SEABED-STRUCTURE INTERACTION
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Intrinsic to the topic of Seabed-Structure Interaction (S-SI) of objects coupled with the sea floor is the dynamics of the "system." The dynamic process include environmental forcing of the object and the seabed, the fundamental properties of the geological material, the size and shape of the object, and the time-dependent processes associated with the coupling of the water column, seabed, and the object. Thus, the most crucial S-SI research problems to address in the Coastal Benthic Boundary Layer Special Research Project (SRP) should focus on the dynamic and time-dependent processes affecting objects coupled to the sea floor. The research efforts should include a range of scales from micro to macro but largely focused on the dynamic processes in proximity to the object rather than broad scale geological and oceanographic processes. Much is to be gained by interdisciplinary research well focused on specific S-SI phenomena.

The S-SI Workshop addressed two important technical topics: (1) Sediment Transport: Scour and Fill, and (2) Geotechnical: Seabed Mechanics. Numerous research topics were identified in each of the two technical areas and additionally two general subtopics were identified as (A) Object Sensing Methods (Detect/Classification) and (B) Sediment Properties Measurements and Data Analysis. Although important to the understanding of S-SI processes, these two subtopics will be thoroughly developed by other SRP workshops and the details will not be discussed here. The most important topics recommended to be part of the SRP, S-SI basic research program, are outlined below.

The purpose of the R&D in Sediment Transport, Scour and Fill, is to improve existing models and create new reliable models of Wave-Current-Seabed-Structure Interaction (W-C-S-SI). This is to be accomplished through quantitative studies of the combined effects of W-C-S-SI directed at understanding the dynamics of the coastal environments and time-dependent processes. Studies should include all sediment types common to coastal environments; sands, silts, clays and organic rich deposits, and mixtures of each.

Sediment Transport: Scour and Fill

- o Development and testing of physical models incorporating the time-dependent S-SI interactions. Small-scale and full-scale studies are needed.

- Understanding of scaling effects and scaling laws involving S-SI processes; facilitated by laboratory and field studies.
- Understanding of the turbulent hydrodynamic variations (small to large scales) induced by the presence of an object in the flow field.
- Understanding of the nonlinear wave-current interactions with the sea floor and the object coupled with the sea floor.
- Understanding of the time scales and transient phenomena driving and controlling pore water flow in proximity to bottom-sitting objects in dynamic motion.
- Understanding the role of dynamic pore pressure on sediment transport and stability around a solid body coupled with the sea floor (muds and sands) and driven by different (frequency) environmental wave-current forces.

The purpose of the R&D in Geotechnical, Seabed Mechanics, is to create a reliable predictive model of the object-seabed mechanical interaction. The sediment reactions are a combination of:

(a) stresses and deformations caused by direct interactions between seabed and object.

(b) stresses and deformations caused by the regional hydrodynamic field.

The effects of the combined system (a)(b) are exhibited by a range of phenomena

1. static—no deformations—object at rest
2. slow settlement and displacements of supporting sediment
3. rocking, gap development, self-embedment
4. sliding, gouging, etc.

To accomplish development of a reliable model, studies are required in diverse areas of sediment structure interactions.

<u>Geotechnical: Seabed Mechanics</u>

- Understanding of the processes responsible for gap formation in cohesive sediments by object/sediment/fluid interaction.
- Understanding of the role of gas charged sediment in the dynamic behavior of object-sediment coupling.
- Understanding of the wave-induced sediment deformations stresses and pressures (total stress and pore pressures) of objects in dynamic motion on a clayey (mud) sea floor when object is allowed to rock, sway, heave, etc.
- Understanding of the development of excess pore pressure and degradation of sediment strength under dynamic loading conditions with object coupled with the seabed; the importance and influence of permeability, sediment type (grain size and mineralogy), and microfabric on the time-dependent processes.

- Understanding of wave induced pore pressure attenuation with subbottom depth in sands, silt, clays and admixtures and an understanding of the energy transfer in different sediment types under various wave climates in coastal areas.
- Understanding and development of modeling laws for scaling from laboratory tests to field conditions.

The above topics will largely dictate what types of instrumentation are required in developing laboratory and field studies and what specific environmental data and seabed properties measurements are needed.

SEABED-STRUCTURE INTERACTION

INTRODUCTION

Background...The topic of Seabed-Structure Interaction (S-SI) is one of four crucial research elements in the Coastal Benthic Boundary Layer Special Research Program (SRP). The program is designed to address important basic research issues directed toward support of the U.S. Navy's coastal, mine counter measures (MCM), and amphibious mine warfare (AMW) operations. The other three topics of interest to the SRP include (1) Environmental Processes and High Frequency Acoustic Scattering/Propagation Phenomena at the Benthic Boundary Layer, (2) Sediment Classification Methodologies Required for Improved MCM Systems Performance and Performance Prediction, and (3) Processes Responsible for Fine-Scale Electro-Magnetic and Electro-Optical Variability in Near Shore Marine Sediments. These three topics are not directly addressed in this report although the basic research involved in each of the four topics has important synergism that supports the Coastal Benthic Boundary Layer SRP. The research thrust that links the four major research topics is the objective to improve the performance and performance prediction of MCM systems used to detect, classify, and neutralize mines located within or on the sea floor. This is accomplished through basic research directed toward understanding environmental processes that affect MCM and AMW operations in coastal waters.

The technology issues involving S-SI processes include the predictions of mine burial at impact and by scour, sand wave migration, and deposition including well defined but poorly understood S-SI mechanisms. A host of technical problems exist for basically all marine sediment types including sands, silts, clays, and admixtures of each. The environmental processes and the types of data requirements necessary for addressing technical problems in S-SI have been summarized by Valent et al. (1988) (Tables 1 and 2). The complex marine environment combined with the high spacial and temporal variability of sediment properties and processes, at the sediment-water interface and within the seabed, provides a unique challenge for future research on the subject of S-SI.

The coupling of an object with the seabed and their combined dynamic response is described as S-SI. Implicit in the definition of S-SI is the importance of the forcing by and the interaction with hydrodynamical processes in the benthic boundary layer. Because the marine environment is characterized by a variety of geological materials, seabed properties, and hydrodynamic processes, the problems of modeling, analysis, and prediction of S-SI time-dependent processes are complex; and thus present capabilities that are

Table 1.1-1. Potential S-SI problems for consideration.

Environmental Processes (mass processes)

- Bottom failure (without structure on bottom)
  - — Environmental forcing functions, e.g., waves, earthquakes (seismic shock), internal waves
  - — Scour-oversteeping by sedimentation (may be seasonal), bioerosion, iceberg keels
  - — Strength decrease: pore pressure increase due to:

    waves
    osmotic pressure changes
    biogenic methane production
  - — External, man-induced: ships, construction activities, weapons effects (shock waves, etc.)
  - — Tide-induced flow slides (sands / silts)
  - — Collapse of bottom due to environmental conditions (little or no translation)
- Nepheloid layer (high-density bottom water)
- Sand wave migration due to storms
- Changes in water column characteristics due to differences in bottom characteristics (properties), i.e., wave degradation characteristics, water velocity, pressure

Processes Due to Structure on Bottom (localized processes)

[structure configuration (effects of) and changes produced by currents and waves]

- Scour: sand/silt/clay scour resulting in the following:
  - — settling
  - — tilting
  - — movement
  - — burial, differential settling
- Localized strength degradation and pore pressure changes due to repeated loading (cyclic loading of structure on bottom)
  - — thermal gradients (frozen ground/permafrost) freeze-thaw
- Bottom failure/bearing capacity
  - — initial failure and failure due to strength degradation
  - — prediction of penetration depth
  - — breakout forces required
- Settlement - consolidation
- Prediction of skidding and sliding

Table 1.1-2 Data requirements for S-SI analysis.

Soil Properties (required for all stratigraphic units)

- Noncohesive sediment
  - — Grain size (mm)
  - — Specific gravity and water content
  - — Bulk density
  - — Angle of internal friction (on effective stress basis obtained from direct shear or triaxial tests)
  - — Permeability
  - — Relative density
- Cohesive sediments
  - — Grain size (mm)
  - — Specific gravity and water content
  - — Atterberg limits (liquidity index)
  - — Bulk density
  - — Undrained shear strength (by miniature vane or unconfined compression - UU)
  - — Remolded strength/sensitivity
  - — Consolidation and permeability data
  - — Consolidated undrained shear strength (on effective stress basis with pore pressure measurements, CU - test)

Environmental Data (required for all sites)

- — Bottom slope
- — Wave climate and currents
- — Water depth
- — Water density (salinity)
- — Bottom roughness

Structure Data

- — Size, shape, and weight
- — Footprint/configuration/shape
- — Static and dynamic bearing pressure on footings (secondary vibrations)
- — Influence of structure on currents and waves around footings

In Situ Data

- — Cone penetrometer resistance
- — Pore pressures
- — Vane shear strengths
- — Resistivity/conductivity

(from Valent et al., 1988)

unreliable for critical Navy applications. Four fundamental S-SI processes, Shakedown, Skidding and Lateral Motion, Scour and Fill, and Dynamic Penetration, are identified in this report, and the related research issues recommended are directed toward gaining a fuller understanding of the basic mechanisms and environmental processes important in the dynamic coupling of the sea floor and an object (Figures 1 and 2). By definition, **Shakedown:** is a dynamic bearing capacity process due to cyclic loading by waves and currents (objects experiencing penetration under cyclic loading conditions [complex dynamic effects]); **Skidding and Lateral Motion:** is considered here for small normal loads when the object experiences lateral movement or skidding; **Scour and Fill:** removal and/or deposition of sediment around an object (static or in motion) that may experience burial or net transport; **Dynamic Penetration:** the dynamic penetration of an object into the seabed at various entry angles and velocities and the response of the sediment to deformation (stress and strain). Scientific issues and research thrusts are directed toward understanding the physics and modeling of the benthic boundary layer processes (with and without bottom sitting objects), time-dependent changes in the environment and sediment response, and their impact on the sea floor properties as they affect MCM operations.

Purpose... This report is a result of a one and a half day workshop on the subject of S-SI convened in Metairie, LA in November 1991. The meeting was attended by professional engineers and scientists from academia, government, and industry. Technical disciplines represented at the workshop included marine geology and geotechnique, sedimentology, oceanography, fluid dynamics and hydraulic engineering, signal processing, and physics and modeling, which provided a strong interdisciplinary forum. The purpose of the workshop was to identify important research issues that require additional research on the topic of S-SI in support of the Navy's Coastal Benthic Boundary Layer SRP. Names and affiliations of the participants who attended the S-SI workshop are included in Appendix A.

Organization of Workshop and Report... During initial deliberations on the topic of S-SI by the workshop attendees, the decision was made to organize the workshop into two technical groups to address interrelated but discipline oriented subject areas. Group One was identified as the Sediment Transport: Scour and Fill technical group and Group Two was the Geotechnical: Seabed Mechanics technical group. Members of each group are identified in Appendix B. Leaders were Steven Hughes, CERCWES, for the Sediment Transport group and James Hooper, Fugro-McClelland, for the Geotechnical group. The rationale for this division was for the purpose of focusing on specific technical issues by experts most closely associated with the required disciplines. Linkage and synergism between the two groups were maintained by regrouping

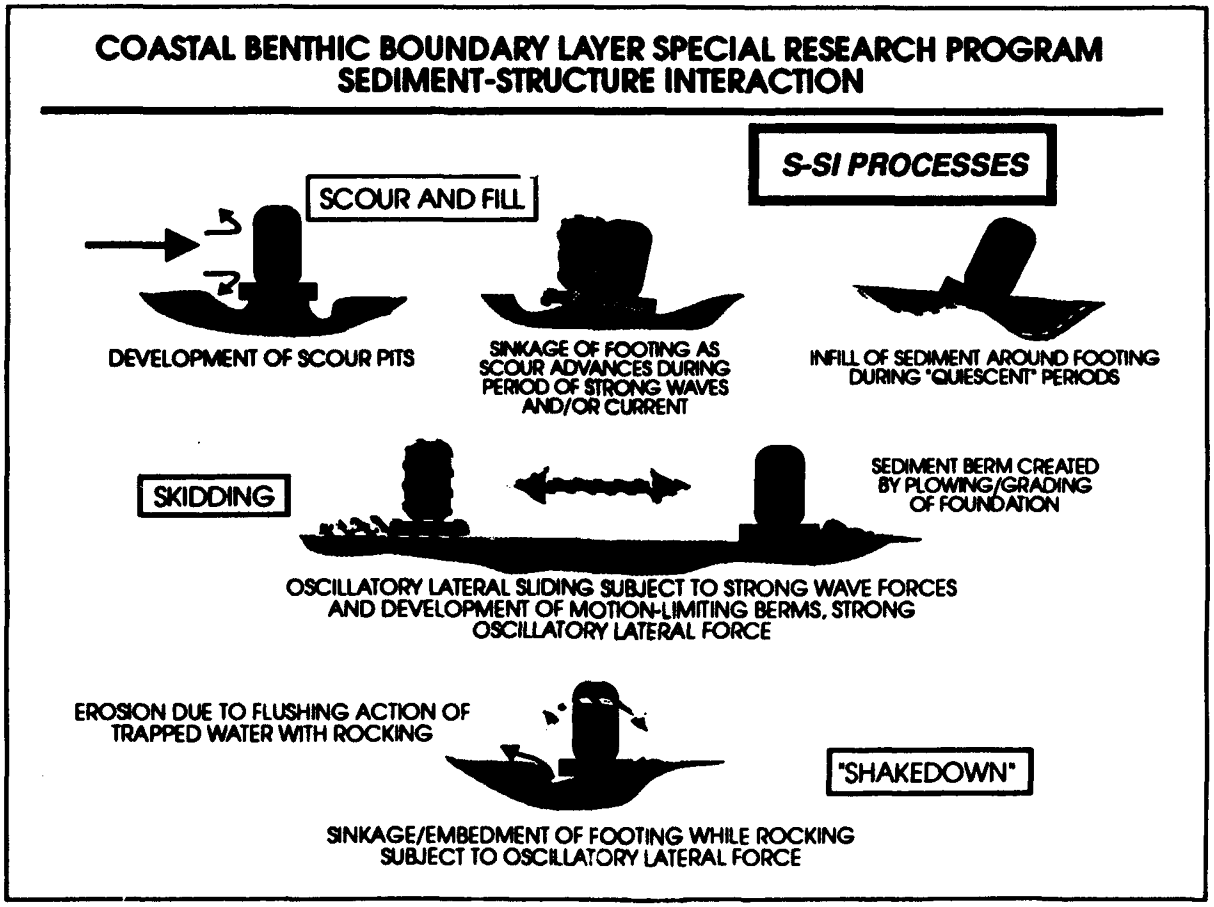

Figure 1. Sediment-structure interaction processes involving the coupling and dynamic interaction of an object and the seabed driven by complex environmental forces that vary with time. (Modified from Valent et al., 1988. Does not represent actual mine configurations; rather depicts particular sediment-structure interaction processes and mechanisms.)

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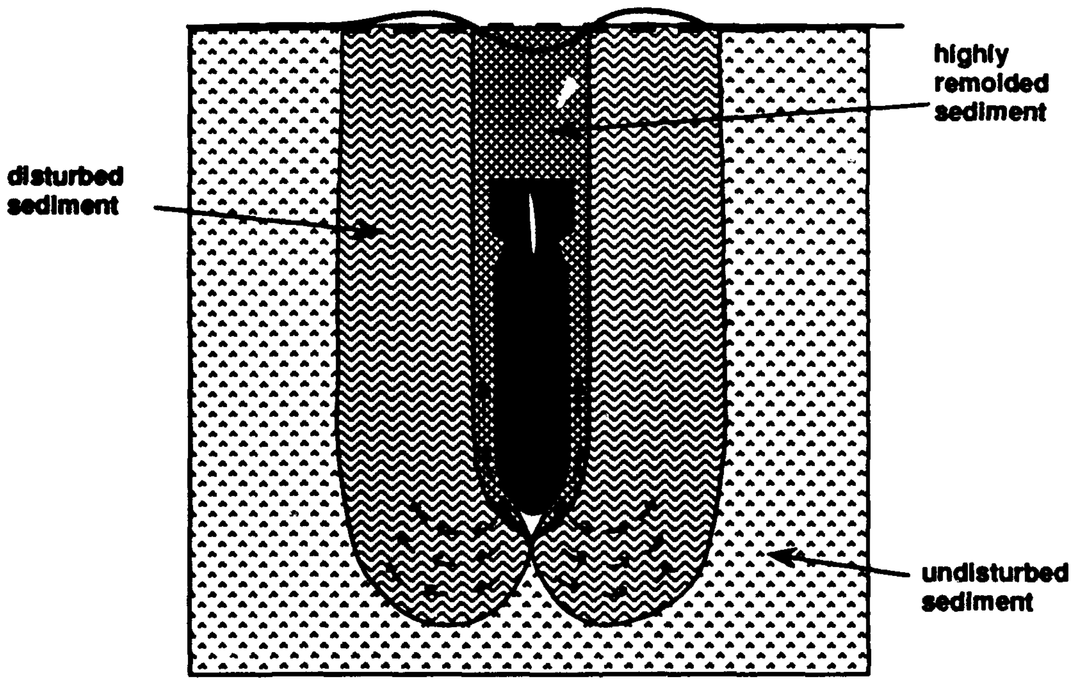

Picture of Penetrator

Figure 2. Sediment-structure interaction of an object penetrating the seabed, involving complex sediment remolding - deformation, pore pressure response and time-dependent changes in sediment properties. (Compliments of Phillip Valent)

all participants during the workshop to discuss technical issues identified by the two separate groups. Thus, this report is organized in two parts; recommendation for research in (1) Sediment Transport; Scour and Fill, and (2) Geotechnical: Seabed Mechanics. The methodology and organization proved successful and resulted in the recommendations identified in this report. It is anticipated that this report will provide a springboard for future research on the coastal marine environment in the important subject area of S-SI processes and mechanisms.

SEDIMENT TRANSPORT: SCOUR AND FILL

BACKGROUND

Seabed-Structure: Scour and Fill

Scour that occurs around a solid body resting on the sea floor, and the partial or complete subsequent burial of the body, is dependent upon the complex interaction of the fluid, sediment, and the solid body itself. These interactions include the turbulent hydrodynamic variation induced by the presence of the solid body in the flow, the transport of sediment by the flow, and the response of the sediment bed to the solid body surcharge (loading). Individually, these separate interactions are poorly understood, at best; taken collectively, the combined interactions of the scour process are virtually unknown. Consequently, reliable prediction of seabed scour around a solid body is beyond the current state-of-knowledge.

Fundamental research into the complex fluid/structure/sediment interaction is needed in order to improve our understanding of the scour problem to at least the same level as our present capability to specify the environmental forcing conditions. A crucial aspect of the problem of reliable S-SI predictive capabilities is a fundamental understanding of the nonlinear wave-current interactions and coupling with an object on the sea floor. Complex time-dependent interactions exist and reliable physical models are urgently needed.

The following list details those aspects of the solid body/scour problem where physical understanding and research are most needed. Several of these research issues are somewhat broad and encompass several separate topics that could be individually investigated. However, it will be important for individual efforts to be well coordinated within each of the research issues.

Research Issues:

1. What are the significant, time-dependent interactions between the small-scale, near-bed, wave boundary layer and the large-scale, benthic boundary layer?

2. How do suspended sediments affect the wave and benthic boundary layer? How does suspended sediment affect turbulence?

3. What is the role of dynamic pore pressures on sediment transport in the vicinity of a solid body resting on the sea floor? What are the time scales and transient phenomena driving and controlling pore water flow in proximity to the bottom sitting object?

4. How does the presence of a solid body impact spacial and temporal 3-D turbulent structure in the water column, and how does it affect the pressure distributions within the bed?

5. How can our understanding of the empirically based coupling between shear stress and sediment transport be improved? Specifically, what is the relationship between the spacial and temporal stress distribution in the wave boundary layer and the suspension and deposition of sediments?

6. How do large- and small-scale bedforms interact with the turbulent flow in the wave and benthic boundary layers?

7. What new methodologies must be developed in order to successfully apply advances in scour mechanics to practical applications?

8. New technology is required for the direct, nonintrusive, measurement of sediment transport in the field. Examples may include infrared optical backscatter sensors and ground penetrating radar.

9. Fluidization of a sandy sea floor: initiation of suspension under nonuniform and oscillatory flows. Effects of local gradients of density, sediment concentration, velocity, pressure and stresses due to waves, turbulence and to the presence of a structure. Possible extension of granular flow mechanics to the dynamics of bedload transport under oscillation and nonuniform flow conditions. Theoretical and experimental advances are needed beyond Meyer-Peter formula for sediment transport rate in steady flows. Collisions among particles are accounted for (S.A. Savage, McGill, and Jim Jenkins, Cornell).

10. Effects of suspended sediments on the structure of the turbulent boundary layer (turbulence intensity variation, vertical structure of Reynolds stresses).

11. The role of large scale (vertical and horizontal) variations on the benthic boundary layer and on the sediment motion within. The large scales may correspond to Ekman boundary layer depth, wavelength of the water wave, or the sandbars. Understanding of the three dimensional structure (velocity and stress) in the wave boundary layer over sandbars or irregular bathymetry is needed and the mechanics of sandbar formation and migration due to large scale variations of boundary layers needs to be more fully understood.

12. Sediment instability, formation and migration of ripples: ripples are due to unstable sand motion under oscillatory flows and are a major source of bottom roughness. Given the amplitude and frequency of an oscillatory flow outside the boundary layer and the grain size, what are the likely sand-ripple wavelengths and ripple heights? How does the role of vortices in the boundary layer affect ripple development? How do the vortices affect scour at the object/sediment-water interface? How is orbital wave particle dynamics in the benthic boundary layer affected by the presence of an object on the sea floor? How do large scale horizontal gradients in the boundary layer, due to a structure of surface waves of the order of 100 m, affect ripple development and migration? How do ripples on large bars develop and affect the formation and movement of the bars?

13. Dynamics of cohesive sediments in and below the wave boundary layer.
    A. Fluidization of cohesive seabed
    B. Bulk motion of fluid mud due to nonuniform gradient and transients.
    C. Instability of a muddy seabed, with or without a structure.
    D. Non-Newtonian rheological behavior of fluid mud.
    E. Time-dependent response of sediment pore water pressure as a function of surface wave activity and the response of pore pressure as a function of the combined effects sediment-structure dynamics and surface wave activity. These processes are poorly understood especially for complex sediment types with admixtures of sand, silt, and clay that are common in the marine coastal environments.

    F. Dynamic behavior and properties of soft mud possessing total organic contents of greater than 2% (>2% TOC). Rheological behavior, cohesion, compressibility, physical properties, erodibility, etc., in relation to depositional environment, sediment type, mineralogy, and microfabric.

GEOTECHNICAL: SEABED MECHANICS

BACKGROUND

Geotechnical: S-SI, Properties, and Sensing Methods

The mechanics of Sediment(seabed)-Structure Interaction phenomena are poorly understood particularly with regard to the coupling processes and mechanisms and time-dependent changes in the seabed as a function of the dynamics of the sediment-structure system and the energy of the environment. The processes and mechanisms are complex and additional research is required to develop reliable predictive capabilities for the response of objects coupled with the sea floor.

Important research areas of investigation that would improve modeling and predictive capabilities include factors such as scaling effects, penetration rate functions, dynamic forces, coupling phenomena, and strength degradation effects and the significance of these factors on the analyses of penetration, sinkage, sediment liquefaction and pumping, and punch-through. Punch-through is a problem in layered sediments where the bearing resistance of a stiff surficial layer is exceeded and the object "punches through" into a soft underlying layer. These geological conditions can occur in coastal environments and are a result of changing environmental conditions and changes in source material. The physics and modeling of dynamic penetration of objects into the seabed is another area where research is required and has particular importance to problems in mine warfare. Reliable models for layered sediments are sorely needed particularly in cases of punch-through and dynamic penetration of objects in seabed sediments.

An important topic of research related to Sediment(seabed)-Structure Interaction is in the area of object sensing methods and detection of structures on and buried within the seabed. New technologies that offer rapid means of detection with high resolution are crucial to Naval applications.

Three broad technical areas were discussed by the Geotechnical Group and research recommendations and issues were identified. The three areas included, (1) Sediment(seabed)-Structure Interaction, (2) Sediment Properties and Processes, and (3) Object Sensing Methods. Object Sensing Methods will be covered in greater detail in another SRP workshop, but the topic is covered briefly here because of its importance to S-SI processes and technical issues.

I. Sediment-Structure Interaction

<u>Research Issues</u>:

1. Prediction of threshold loading for gap formation.
2. Prediction of object/sediment/fluid interaction for cohesive sediments (in particular at gap between sediment and object).

   On a clayey (mud) sea floor:
   a. Burial of a structure into the soft bed by self weight. Large amplitude nonlinear deformation.
   b. Wave-induced sediment deformation stresses and pressure when the structure is allowed to move (sway, heave, rock, etc.). Nonlinear constitutive behavior of clayey sediment should be considered (under undrained condition).
   c. Current-induced stress and pore pressure and sediment deformation in a nonlinear sediment.
3. Prediction of skidding vs. sinking (gouging).
4. Development of excess pore pressure under dynamic loading (local effects).
5. Dynamic sediment-rheology/viscoelastic wave-structure interaction.
6. Evaluation of forcing function and dynamics on seabed objects.
7. Self-weight sinkage-static and dynamic loading.
8. Effect of gassy sediments on sinking.
9. Object implanting by bioturbation.
10. Develop modeling laws for scaling (lab to field).
11. Modeling variations of engineering properties of sea floor sediments; evaluate their effects/influence on S-SI.
12. Prediction of fluid/sediment structure interaction (cohesionless sediment)
13. Refine analytical models for projectile penetration. Dynamics of penetration of mine into a viscoelastic sediment.

II. Sediment Properties and Processes

<u>Research Issues</u>:

1. Bioturbation effects on material types and on micro and macro variability of properties.
2. Diagenesis is a process and important factor in the lateral and vertical variability of sediments and it is important in cement types and effects on sediment properties. Processes are poorly understood in relationship to environments of deposition, various sediment types and oxic and anoxic environments.
3. Gas/Sediment compressibility/strength/moduli; Gas bubble mobility in soft clay/loose sand.
4. Excess pore pressures under dynamic loading (including

gassy sediment); different sediment types, environments, and wave loading. Attenuation of pressure signal with subbottom depth and time-dependent changes in excess pore pressure.

5. Pore pressure in Oxidation/Reduction zones caused by microbiological activity and in gassy sediment.
6. Degradation of vessel signatures by sediment; Change in neutralization explosion pressure in sediments.
7. Thermal signal properties of geological materials.

Measurements of Sediment Properties and Data Analysis:

1. Determination of sediment properties
   a. Using surface shear waves.
   b. Tools and analysis methods for resistivity of fine-layered sediments (probe).
   c. Tools and analysis for thermal pulse method for sediment classification and detection.
2. Classification of sediment properties by side scan sonar; estimation of sediment properties (geotechnical) by other remote detection methods.
3. Perceptual science (i.e., artificial intelligence) to characterize sea floor properties.
4. Tomography for data correlation.

III. Object Sensing Methods (Detect/Classification)

Research Issues:

1. Detection of objects with properties similar to sediment properties.
2. Diffraction pattern recognition of objects.
3. Discrimination of objects on sea floor.
4. Multimode scanning of objects.
5. Rapid rate of areal coverage.
6. Discrimination of manmade vs. natural objects.
7. Exploitable penetrating radiation.
8. Detection of objects by shear wave propagation.
9. Cataloging of object signatures in various sediments.

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Intrinsic to the topic of Seabed-Structure Interaction (S-SI) of objects coupled with the sea floor is the dynamics of the "system." The dynamics involve environmental forcing of the object and the seabed, the fundamental properties of the geological material, the size an shape of the object, and the time-dependent processes associated with the coupling of the water column, seabed, and the object. Thus, the most crucial S-SI research problems to address in the Coastal Benthic Boundary Layer Special Research Project (SRP) should focus on the dynamics and time-dependent processes affecting objects coupled to the sea floor. The research efforts should include a range of scales from micro to macro but largely focused on the dynamics and processes in proximity to the object rather than broad scale geological oceanographic processes. Much is to be gained by interdisciplinary research well focused on specific S-SI phenomena.

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